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GALACTIC POPULATIONS OF ULTRACOMPACT BINARIES

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ABSTRACT

Recent *RXTE* and *Chandra* discoveries of low mass X-ray binaries with ultra-short orbital periods have initiated theoretical work on the origins of these peculiar systems. Using the *StarTrack* population synthesis code the formation and evolution of X-ray ultracompact binaries (UCBs) in the Galactic field are analyzed. The relative number of UCBs with a neutron star or a black hole accretor populating our Galaxy is predicted. Our results demonstrate that standard evolutionary scenarios involving primordial binaries can be sufficient to produce the UCBs in the Galactic field without requiring additional processes associated with the dense stellar environments in the cores of globular clusters. In contrast to previous studies we find that the majority of the immediate progenitors of these systems consist of a hydrogen exhausted donor with an ONeMg white dwarf. The evolution of these systems leads to the accretion induced collapse of the white dwarf to a neutron star, which can play an important role in the formation of a majority of Galactic UCBs. We predict that with an increase in the number of X-ray active UCBs hosting neutron stars by an order of magnitude, a system with a black hole accretor may be found.

Subject headings: binaries: close — stars: evolution, formation, neutron — X-rays: binaries

1. INTRODUCTION

Recent discoveries have revealed that the X-ray binary population of the Galaxy extends to orbital periods as short as 20 minutes. Their existence in both the Galactic field and in the dense stellar environments in globular cluster systems has motivated theoretical work on their formation and evolution. The class of previously known ultra-short period systems known as AM CVn systems are generally believed to consist of a white dwarf (WD) accreting material from another degenerate white dwarf or from a low mass semi-degenerate companion (for a review, see Warner 1995). In contrast, the X-ray emitting systems, some of which are millisecond pulsars, contain a neutron star (NS) accretor and, most probably, a degenerate low mass donor. To date, only 4 systems are confirmed while another 4 are strong candidates of UCBs with a NS accretor in the Galactic field (Chakrabarty 2003). So far, no system with a black hole (BH) accretor has been discovered.

There are three proposed scenarios of UCB formation, involving the evolution of a NS-WD or NS-He star binary (descendant of a common envelope episode), or the mass transfer (MT) from an evolved main sequence (MS) donor to a NS. Although the ultracompact phase has been studied in detail (Tutukov et al. 1987; Rasio, Pfahl & Rappaport 2000; Yungelson, Nelemans, & van den Heuvel 2002; Nelson & Rappaport 2003; Deloye & Bildsten 2003), the prior evolution of progenitor systems was usually assumed or only briefly discussed in different contexts (e.g. Nelemans, Yungelson & Portegies Zwart 2001). Our analysis of possible evolutionary channels leading to the formation of the UCBs with NSs and possibly BHs shows the limitations of such an approach. We point out in the following sections that a large fraction of NS-WD systems evolve first through NS-He star MT phase, with a NS forming predominantly via an accretion induced collapse (AIC) of a white dwarf. In addition, we show that the NS-MS formation channel is less important for the overall production of UCBs.

2. MODEL DESCRIPTION

The calculations are based on a binary population synthesis method. The *StarTrack* code (Belczynski, Kalogera, & Bulik 2002) has recently undergone major revisions and updates (Belczynski, Kalogera, Taam & Rasio 2003, in preparation), among which include: detailed treatment of tidal synchronization and circularization, individual treatment of various MT phases, full numerical orbit evolution with angular momentum losses due to magnetic braking, gravitational radiation (GR), mass transfer/loss and tides, and incorporate the stabilizing influence of optically thick winds on accreting white dwarfs (Hachisu, Kato, & Nomoto 1996) allowing for growth of different types of WDs to either the disruption of the white dwarf in a Type Ia supernova explosion or to the formation of a NS via AIC (see Li & van den Heuvel 1997; Ivanova & Taam 2003). For the accumulation of helium or carbon/oxygen matter on CO or ONeMg WDs, we make use of the helium accumulation efficiencies determined by Kato & Hachisu (1999) and the off center ignition results of Kawai, Saio, & Nomoto (1987) in determining the fate of the underlying WD.

A large sample of single (10^6) and binary (10^6) stars in the Galactic field are evolved for 10 Gyrs assuming a constant star formation rate. The more massive primaries of the binaries (and single stars) are drawn from an initial mass function with a slope of -2.7 within the range of $4 - 100$ M$_\odot$, while the less massive secondaries of the binaries are taken from a flat mass ratio distribution within $0.08 - 100$ M$_\odot$. Here, the mass ratio, q, is defined

as the mass of the secondary to the primary. The initial binary separations are taken from a distribution flat in the logarithm up to 10^5 $R_\odot$, while we assume a thermal equilibrium distribution for the eccentricities. All stars are evolved based on the results of Hurley, Pols, & Tout (2000) for models with a solar metallicity. We adopt parameters corresponding to the standard model of Belczynski, Kalogera, & Bulik (2002), changing the maximum NS mass to 2 $M_\odot$, incorporating the latest natal kick distribution of Arzoumanian, Chernoff & Cordes (2002), and limiting the accretion rate onto the NS and the BH at the maximum Eddington limit with the rest of the transferred material lost with specific orbital angular momentum of the accretor during the dynamically stable MT events, but allowing for hyper-critical accretion at common envelope (CE) phases. Besides the dynamically unstable MT events we also allow for evolution into the CE phase in cases in which the trapping radius exceeds the Roche lobe radius of the accretor (e.g., King & Begelman 1999; Ivanova, Belczynski, Kalogera, Rasio & Taam 2003).

3. RESULTS

Since the entire spectrum of binaries and single stars are produced by our calculations we shall adopt as a working definition for UCBs any system in which mass is transferred to a NS or a BH at orbital periods less than some value. For definiteness, 80 minutes is chosen as a customary value, but 5 hours is also used for a broader definition.

3.1. *Formation Channels*

The various UCB formation channels realized in our *StarTrack* evolutionary model are presented in Table 1. The majority of UCBs are formed with a NS accretor, in particular along the channel NS:01. A typical progenitor system corresponds to an intermediate mass primary and low mass secondary in an orbit sufficiently wide such that the primary evolves up to the asymptotic giant branch stage prior to filling its Roche lobe. The ensuing MT is dynamically unstable, leading to the formation of a CE (see Iben & Livio 1993; Taam & Sandquist 2000). Systems emerging from the CE phase consist of an ONeMg WD (descendant of primary) and a MS secondary at an orbital separation such that the secondary can overfill its Roche lobe while expanding in the Hertzsprung gap or the first giant branch. The further evolution leads to a second CE phase. Provided that the system avoids merger the remnant system consists of an ONeMg WD and a low mass He star or WD companion. Hence, initially wide systems become very tight after the successful ejection of mass in the two common envelope phases. The secondary fills its Roche lobe for a second time due to the action of angular momentum losses associated with GR emission and, for sufficiently massive He stars, stellar expansion induced by nuclear evolution. However, in this Roche lobe overflow phase, the two components of the system are of comparable mass and the mass transfer proceeds stably. Provided that the mass transfer rates exceed a critical value such that the the accreting WD accumulates sufficient matter to exceed the Chandrasekhar mass, a NS may form by the AIC process as discussed by Taam & van den Heuvel (1986) and Webbink (1992) for the formation of low mass X-ray binary systems. More recently, Yungelson, Nelemans, & van den Heuvel (2002) described the formation of the UCB X-ray pulsar 4U 1626-67 in terms of the AIC scenario. In general, the outcome of this formation channel is a UCB system consisting of a He star or WD donor transferring mass to its NS companion.

In contrast to the NS UCBs, there is no single major formation channel for the BH UCB systems. Although the BH:01 dominates in the formation of BH UCBs, the effect is not as strong as in the case of NS UCBs with the NS:01 channel. Close inspection of Table 1 reveals that the NSs in UCBs are either formed through AIC or Type II SN (core collapse and explosion of a massive star). However, the BHs are not formed directly from the core of a massive star, but rather formed in the collapse of the accreting NS when its mass exceeds ~ 2 $M_\odot$. Therefore, the formation channels of BH UCBs without an SN entry, are characterized by two AIC events: a WD to a NS, and then a NS to a BH.

Most of the UCB accretors are formed through AIC of a heavy ONeMg WD to NS ($\sim 80\%$). Contrary to previous assumptions on the type of donor formed in NS-WD systems, the last CE episode results in the formation of not only WD ($\sim 40\%$) but also low mass He-stars ($\sim 40\%$) secondaries. Either the WD or the He-star companion fills its Roche lobe and starts transferring material to the ONeMg WD. The AIC interrupts the MT due to the loss of binding energy of the collapsing dwarf. However, in the case of a He-star donor, MT may restart on a short timescale as nuclear expansion of the He-star is faster in bringing the system to contact than GR in the case of a WD donor. The He-star donors eventually lose sufficient mass to become low mass (~ 0.35 $M_\odot$) hybrid WDs (with a mixture of helium and carbon/oxygen in the core) while the systems enter a long-lived (~ 1 Gyr) UCB phase. These donors, given enough time, may cool down and crystallize, forming a Ne-enriched layer in their interiors (Yungelson, Nelemans & van den Heuvel 2002). The subsequent MT eventually uncovers the deeper layers of the hybrid WD giving rise to a Ne-enriched accretion flow, claimed to be observed in several of the NS UCBs (Juett, Psaltis & Chakrabarty 2001). As our simulations show, a significant fraction of the NS UCBs have hybrid WD donors.

The initial binary parameters of the systems forming UCBs with orbital periods less than 80 minutes are illustrated in Fig. 1. The progenitors of both classes of UCBs with NS and BH originate in a wide range of initial orbital periods and mass ratios. Upon detailed inspection, the initial component masses exhibit traces of correlations. For example, the secondary mass, for BH UCB progenitors, is confined to a narrow range of 4 - 7 $M_\odot$, and although the primary mass spans a wide range, most of the primaries have a mass close to 8 $M_\odot$. On the other hand, the progenitor systems that form NS UCBs are characterized by secondaries mostly within the range of 1 - 5 $M_\odot$, while the primaries concentrate around 7 $M_\odot$. It is natural that the progenitors of BH systems are more massive than the progenitors of NS binaries, however, contrary to expectation, the separation of the two sub-populations is not well defined, with the two groups partially overlapping. This is a direct consequence of the fact that the BHs are formed from the NSs via the AIC process and, thus their progenitors do not significantly differ from the progenitors of NS UCBs. A few BH accretors in UCBs originate from the

primaries of ~ 30 $M_\odot$, which is not shown in Fig. 1.

3.2. *Evolution at Ultracompact Phase*

At the short orbital periods characteristic of the UCBs, its evolution is governed by the mass and angular momentum loss from the system. The orbital evolution is dependent on the fractional amount of matter which is ejected from the system, angular momentum losses associated with this ejection of matter and GR or magnetic braking, as well as the possible nuclear evolution of the donor.

An example of the evolution for one particular BH UCB is illustrated in Fig. 2. In this example, the system enters the ultracompact phase via channel BH:02. The system emerges from the second CE phase as a binary composed of a 1.2 $M_\odot$ main sequence helium star and a heavy ONeMg WD companion of ~ 1.4 $M_\odot$ orbiting about their common center of mass with a period of about 1 hour. The helium star initially transfers material at a rate of $\sim 8 \times 10^{-8}$ $M_\odot$ yr^{-1} and very quickly the accreting WD collapses to form a NS. In our present calculations we assume that there is no natal kick associated with the AIC process. The MT rate initially exceeds the Eddington limit for the NS accretor, but soon thereafter decreases and the NS accumulates the material efficiently. The evolution in this phase is similar to the evolution of a helium star - NS system as calculated by Savonije, de Kool, & van den Heuvel (1986). After about 30 Myrs into the MT phase, the NS exceeds 2.0 $M_\odot$ and a second AIC takes place, with the NS collapsing to form a BH. As the MT continues, the He star loses most of its mass eventually becoming a degenerate low mass hybrid WD. The system becomes detached and the MT terminates. Since the onset of ultracompact MT phase, the orbital period has decreased from 60 to about 20 minutes, as mass and angular momentum were lost from the system. The calculations reveal that the MT phase was interrupted briefly as the donor became degenerate, with the subsequent evolution leading to the increase in the orbital separation as the donor expands. Although the MT rates are initially high, they very soon become sub-Eddington. It should be pointed out that the detached phase is a result of our simplified treatment of the transition of the donor from a semi-degenerate to a degenerate state. However, the evolution of the system, especially at later times, is not significantly affected by this treatment. Eventually, the WD has been reduced to 0.09 $M_\odot$, marking the end of the rapid evolution of the system. In an additional 1 Gyr the MT rate slowly decreases to $\sim 10^{-12}$ $M_\odot$ yr^{-1}, and the period slowly increases to ~ 70 minutes until the WD reaches the mass of 0.01 $M_\odot$ at which point our calculations were terminated. We note that although finite temperature effects of the WD on the MT have not been taken into account (cf., Deloye & Bildsten 2003) this evolution should be indicative of NS and BH UCBs formed via this channel.

In the above example the system becomes a transient X-ray source, when the MT rate falls below certain critical value (see Menou, Perna, & Hernquist 1999; marked on Fig. 2). In our standard simulation we have assumed that all the material transferred during the transient stage is accreted by the compact star (NS or BH). However, it is possible that little material is accreted during the transient outburst stage. Had we assumed that accretion was not effective during this stage in our example, the results would have been unchanged since the NS already had accreted sufficient matter to become a BH prior to the system entering the transient stage.

3.3. *Content of Current Population*

The population of NS/BH UCBs formed in the disk of our Galaxy at the current epoch (t=10 Gyrs) is listed in Table 2. Systems with NS accretors dominate the population (80%), however there is a non-negligible contribution of systems with BH accretors (20%). The majority of the systems (both with NS and BH accretors) have WD companion donors. As expected for systems with orbital periods less than 80 minutes the only other donors found are low mass He-stars ($M \leq 2$ $M_\odot$). Many of the systems with WD donors have evolved through the phase when the donor was a He-star. However this phase is extremely short lived (by about 2 orders of magnitude less than with WD donors, see Fig. 2), and therefore would be difficult to observe. BH UCBs may also evolve through a phase with a He-star donor, but for these systems the lifetimes at this phase are even shorter (due to the lower mass of the He-star donors) than in case of NS UCBs and are not detected in our simulated observed sample (see Table 2). For longer period binaries some BH UCBs (or heavy NS UCBs had we raised the maximum NS mass to 2.5 $M_\odot$ – see below) may be fed by low mass MS donors. Interestingly, we find that few NSs (below 10%) in our population of UCBs are born in SN explosions, but are preferentially formed in AIC of heavy accreting ONeMg WD. The case is more extreme for BH UCBs, for which all the BHs are formed without a SN explosion through the AIC of a heavy accreting NS.

Systems with orbital periods less than 5 hours, but above 80 minutes are BHs or heavy NSs with MS donors. These binaries evolve as proposed by Podsiadlowski, Rappaport, & Pfahl (2002), starting as intermediate mass systems. After a CE phase, the primary forms a NS in a SN explosion. A MS secondary of $2-4$ $M_\odot$ initiates MT at an orbital period of about 0.5 day. Prior to reaching a period of 5 hrs the NS mass exceeds 2 $M_\odot$, and it collapses to form a BH (this explains the absence of NS-MS systems with periods shorter than 5 hrs in our sample of UCBs). As the mass of the MS donor decreases, the orbital period decreases further near to the point at which the donor ceases nuclear burning in the core (corresponding to a mass lying between 0.08 $M_\odot$ for a unevolved main sequence star to 0.35 $M_\odot$ for an initially non degenerate helium core). Subsequently, the donor becomes a degenerate WD and the MT causes an increase of the orbital period (up to ~ 60 min or longer) until the exhaustion of the donor (e.g., BH:06 formation channel). Although these systems may constitute a tenth of BH UCBs, they give only a small contribution to the entire NS/BH UCB population (less than a few percent).

In order to assess the uncertainty of our predictions, we have calculated several additional models with different assumptions on our input physics. In one calculation we have relaxed the assumption of full accumulation during the transient stages, and have assumed that no material is accreted during these stages. The results of that calculation show only a slight change of the UCB population,

increasing the relative number of NS to 83.7% and decreasing the relative number of BH to 16.3% of the total UCB population.

Yet another limiting factor for the formation of BH UCBs is the adopted maximum NS mass. The maximum mass has been estimated to be in the range of $1.8-2.3$ M$_\odot$ (see Akmal, Pandharipande, & Ravenhall 1998) in comparison to an assumed maximum of 2 M$_\odot$ in our standard calculation. However, most of the BHs in UCBs have rather low masses ($2-2.5$ M$_\odot$), and an increase in the maximum mass has a significant effect on the BH population. An increase of the maximum NS mass to 2.5 M$_\odot$ enhances the population of NS UCBs to 1.2, and reduces the expected number of BH UCBs to 0.1 ($P_{orb} \leq 80$ min) or to 0.2 ($P_{orb} \leq 5$ hrs) of the standard model number.

At least one more factor may affect the BH population. We have assumed that NSs may accrete all the transferred material up to the Eddington limit. This assumption led directly to the formation of BH systems, since some of the accreting NSs were able to accumulate enough material to collapse to BHs during the long lived MT episodes. Had we relaxed that assumption, and allowed all the material to escape the systems, we would end up with no BH UCBs in our population. However, neither the number of NS UCBs nor our conclusions about dominance of AIC systems in the current UCB population would be significantly altered.

Although there may be sufficient energy to eject the CE, the envelope in less evolved phases may not be sufficiently distended to significantly decelerate the spiral in process before the companion merges with the evolved core. Hence, those systems with less evolved donors which evolve into the CE phase may merge rather than survive. We estimate the reduction of systems entering into the UCB phase by assuming that donors which enter into the CE phase in the Hertzsprung gap do not survive. In this case, the number of NS UCBs is not significantly reduced, decreasing to 0.7 of the standard model number, however the BH UCBs would either vanish entirely ($P_{orb} \leq 80$ min) or are reduced to only 0.1 ($P_{orb} \leq 5$ hrs) of the standard model number.

We have also calculated two models with different choices for the efficiency of the common envelope ejection (in our standard model we assume $\alpha \times \lambda = 1$; for details see Belczynski, Kalogera, & Bulik 2002). An increase of the efficiency ($\alpha \times \lambda = 3$) barely changes the results, however, a decrease of the efficiency ($\alpha \times \lambda = 0.1$) drastically reduces the number of the formed UCBs. In particular, the number of NS UCBs (71%) is reduced by factor of ~ 20, while BH UCBs (29%) is reduced by factor of ~ 15. This is easily understood in the framework of the possible formation scenarios of UCBs, many of which involve two episodes of CE. With a decreased efficiency the components of the binary progenitor systems merge, as there is insufficient orbital energy to eject the CE, thus aborting the formation of many UCBs. We note that in this case, the numerical results reveal that all UCBs are formed via the AIC channel.

The formation of ONeMg WDs plays an important role in our calculation since most of our UCBs are formed through the AIC of an ONeMg WD to a NS. The lower mass threshold for ONeMg WD formation is found at an initial stellar mass of 6.4 M$_\odot$ (ONeMg WD mass of 1.2 M$_\odot$) and the high end is at an initial mass of 8.0 M$_\odot$ (ONeMg WD mass of 1.43 M$_\odot$) for a solar metallicity within the framework of single stellar evolution models we use (Hurley et al. 2000). Since the IMF in this mass range ($6-8$ M$_\odot$) is rather steep, most of ONeMg WD are formed with mass close to $1.2-1.3$ M$_\odot$. Our models show that even if the ONeMg WD were formed at a reasonably lower mass, some would be still pushed over the Chandrasekhar mass limit forming NSs and UCBs, due to the sufficient mass reservoir in the progenitor systems.

We have also chosen a different initial condition for our population of primordial binaries. Instead of using correlated initial masses for two binary components (via a flat mass ratio distribution) we have calculated a model in which both masses are drawn independently. Both components were taken within the same mass ranges as before (see § 2). A broken power-law IMF for the stars in the Galactic disk which flattens out for low mass stars is used (Kroupa, Tout & Gilmore 1993). For stars with initial masses $0.08 < M < 0.5$ M$_\odot$ the IMF slope is $\alpha_1 = -1.3$, for $0.5 < M < 1$ M$_\odot$ the slope is $\alpha_2 = -2.2$, while for $1 < M < 100$ M$_\odot$ we use $\alpha_3 = -2.7$. Such a prescription resulted in quite a drastic change of initial mass ratios for our primordial binaries. After independently drawing two component masses for each binary, and recording the resulting mass ratios, we have obtained a distribution peaking below 0.1 and decreasing rapidly so there were almost no binaries with q > 0.4. Such a distribution may be described by $\propto q^{-2.7}$. Due to the extreme mass ratio of most binaries, many of the previous progenitors of UCBs do not survive the first episode of MT as a result of the occurrence of a dynamical instability, leading to merger in the ensuing CE. We note an order of magnitude reduction of number of UCBs formed as compared to our standard model presented in Table 2. This is very similar to findings of Han & Podsiadlowski (2003) who noted the order of magnitude decrease in the formation of Type Ia SNe progenitors with the independent choice of binary component masses. There is also a significant reduction of relative number of systems with BH (6%) as compared to the ones with NS (94%) for $P_{orb} \leq 5$ hrs, with no BH UCBs formed for $P_{orb} \leq 80$ min. The majority of NS systems are found with WD donors, while all BH systems are formed with MS donors close to core hydrogen exhaustion. However, even in this model our population is dominated by AIC systems (~ 90%) as compared to the UCBs with compact objects formed in SNe explosions (~ 10%).

3.4. *Predicted Number of Systems in the Galactic Field*

In this section we address the issue of the predicted absolute number of UCBs in the Galactic field.

Suggestions have been made (Clark 1975; Katz 1975; Verbunt & Hut 1987) that dense stellar environments and, in particular, globular clusters are very efficient in producing LMXBs. The hypothesis was put forward, that most if not all the systems were formed as the result of dynamical interactions in clusters, and then released from the clusters to populate the field (e.g., Grindlay 1984; White, Sarazin & Kulkarni 2002). Different release mechanisms were proposed, including disruption of the clusters in the Galactic tidal field, ejection of systems due to 3- or 4-body interactions, and escape of the binaries with NS due to the

gain of extra systemic velocities in SN explosions.

In the following we will show that the primordial field binaries are sufficient to produce the field NS UCBs (which are the subgroup of LMXB population). Although the formation of such systems in globular clusters is possible, we point out that binary evolution with no dynamical processes involved can account for the entire population of observed Galactic field UCBs.

The calibration of the population synthesis results may be performed in several ways. We choose to obtain absolute numbers using the observed star formation rate in the disk of the Milky Way. However, for consistency calibration is also obtained by comparison of our study to the measured rate of Type II and Ib/c SNe. Galactic SFR have been estimated to lie in ranges of $1-3$ $\mathrm{M_\odot yr^{-1}}$ (Blitz 1997; Lacey & Fall 1985) and $\sim 1-10$ $\mathrm{M_\odot yr^{-1}}$ (Gilmore 2001). Cappellaro et al. (1999) estimated the rates of Type II SN and Type Ib/c SN to be 1.86 ± 0.35 SNu and 0.14 ± 0.07 SNu for Sbc-d galaxies, where 1 SNu corresponds to one SN per 100 yr and the estimates are normalized to a blue luminosity of $10^{10} {L_\odot}^B$. For an estimated Galactic blue luminosity of about ${L_\odot}^B = 2 \times 10^{10} L_\odot$ (van der Kruit 1987) we obtain 1.72 and 0.28 SNu for Type II and Ib/c SN respectively.

Extending our study of stellar masses to the H burning limit ($0.08 M_\odot$) with the use of Kroupa et al. (1993) broken power-law IMF the average (continuous) star formation rate which corresponds to the number of UCBs formed in our sample can be estimated. Comparison with the observed rate requires an upward revision for the numbers presented in Table 2 by a factor of 100 to account for the entire population within the Galaxy. To be conservative, and not to overestimate the number of UCBs formed in the field, we use the lower bound on the star formation in the disk of 1 $\mathrm{M_\odot yr^{-1}}$. The X-ray duty cycle (DC) for transients sources is required, and we adopt $DC \lesssim 1\%$ (Taam, King & Ritter 2000). Only $\sim 1\%$ of our transient systems (listed in Table 2) have a chance to be observed in the outburst state, leading to a reduction by factor ~ 33. We also note the possible further reductions of UCBs due to the largest uncertainties of stellar evolution, in particular CE evolution (factor of ~ 20) and the rather arbitrary choice of initial mass function (factor of ~ 10). Combining all the above factors lead us to estimate the number of active UCBs in the field at the present time to be 7. However, we should understand this estimate as a lower limit, due to our conservative choice of models tending to reduce the predicted number of UCBs. Utilizing the combined observed rate of Type II and Ib/c SN for our calibration results in essentially the same number.

The number of observed confirmed field UCBs hosting NS is 4, with 4 strong candidates and a few additional systems potentially connected to that group. Moreover, there are observational uncertainties since many of the faint X-ray sources have no orbital information, and some may yet contribute to the UCB population. Therefore, one may expect the number of the active field systems to be $\gtrsim 10$, which is consistent with our conservative estimate.

4. CONCLUSIONS

We have calculated the galactic population of short period ($P < 80$ min) ultracompact binary systems and shown that their formation follows from the evolutionary channels of progenitor binary systems characterized primarily by stars of an intermediate mass range ($5 < M/\ \mathrm{M_\odot} < 8$). Although UCBs exist in the dense cores of globular clusters, their population in the Galactic field does not necessarily require their production in these stellar systems. Our population synthesis results reveal that UCB systems with BH accretors as well as NS accretors can be formed with the ratio of the former to the latter systems amounting to 1 - 20% (accounting for a reasonable range of input parameters).

An examination of the formation process of the compact objects in these systems reveals that, in contrast to previous investigations, the immediate progenitors of the majority of UCBs are ONeMg white dwarfs which undergo accretion induced collapse to a neutron star in response to the accretion of matter from hydrogen exhausted companions. This new pathway results in the unexpected potential importance of the accretion induced collapse channel for the majority (90%) of the UCB systems. Similarly, the BHs formed in these systems are not produced directly from the collapse of a massive star, but rather by the accretion induced collapse of a neutron star which has accreted sufficient mass from its companion.

With our adopted IMF slope (-2.7) ONeMg WDs (40%) are formed almost as frequently as NSs (60%). Frequent MT episodes in close binaries further enhance the number of the WDs relative to NSs. However, the most important effect reducing the number of binaries hosting NSs, formed through direct core collapse, are SN explosions which tend to disrupt the binaries (due to the mass loss and natal kicks). Considering the above arguments, and noting that ONeMg WDs are formed with a mass within several tenths of a $\mathrm{M_\odot}$ to the Chandrasekhar limit (so that the mass accumulation during MT required to convert them into NSs is not large) it is understandable why the NS UCB population is dominated by NSs formed through AIC. All BHs in our population of UCBs are formed through AIC. Since BHs formed through SN/core collapse originate from more massive stars, there is only a very small probability that a progenitor system with a low/intermediate mass companion survives a first MT episode, thus aborting this evolutionary channel for the formation of UCBs.

The donors in systems with NS accretors are restricted to helium WDs (60%) and hybrid WDs (40%) with a small contribution from low mass He stars (1%). In contrast, the donors of BH UCBs are hybrid WDs (95%) and CO WDs (5%). For longer period binaries ($P \leq 5$ hrs) there is a small but significant (10%) fraction of MS donors in BH UCBs (or NS UCBs had we raised the maximum NS mass to 2.5 $\mathrm{M_\odot}$).

Those UCBs with NS accretors and He-rich donors are likely to give rise to Type I bursts as a result of a thermonuclear instability on the NS surface. Depending upon the amount of residual hydrogen present on the white dwarf surface superbursts may be produced via thermonuclear burning of the underlying carbon layer (Strohmayer & Brown 2002; see also Taam & Picklum 1978) or due to the photodisintegration of heavy elements produced in the rapid proton capture process (see Schatz, Bildsten, & Cumming 2003). Note, that only those WDs formed from the cores of hydrogen rich stars could be donors for the

photodisintegration scenario, whereas the He WDs formed from the evolution of He stars would lead to the carbon burning scenario for superbursts. For those rare UCBs with CO donors it is possible that they also ignite unstably and may produce a rare, but energetic outburst on the NS.

Many (40%) of the NS-WD systems have evolved through the MT phase with the He-star donor after the last CE phase. As a result these systems host hybrid low mass WDs, which may give a rise to a Ne-enriched accretion flow later in the further evolution of these systems (Yungelson et al. 2002).

Only a small fraction (2.2%) of UCBs are persistent X-ray sources, with X-ray luminosities of $L_x = 7 \times 10^{36} - 3 \times 10^{38}$ erg s^{-1}. The majority of the UCBs are transient X-ray sources (97.8%) with low MT rates of $10^{-11} - 10^{-12}$ M$_\odot$ yr^{-1}. Without a reliable knowledge of the recurrence times we are unable to predict the precise number of active sources at the present time. However, if only a small fraction of them are active (say 0.1) they still would dominate the current population of UCBs, both in number as well as in X-ray brightness with typical peak luminosities of $L_x = 4 - 8 \times 10^{38}$ erg s^{-1} (assuming accretion at the Eddington rate during active states).

Out of 4 observed systems, 2 are transients, one is probably a persistent source, and one is X-ray burster. Moreover, the majority host millisecond pulsars (3 out of 4) and their orbital periods span the range of 40 to 50 minutes. Given the theoretical and observational uncertainties, these observations are not inconsistent with our results. Specifically, more transient sources are predicted than persistent sources, however, about half of the systems (with a He rich donor) are expected to be X-ray bursters. Since most of the NSs have accreted ≥ 0.1 M$_\odot$, the NSs would likely have been spun up to millisecond spin periods. Finally, most of these systems spend 90% of their ultracompact lifetime after emerging from a period minimum at orbital periods $\sim 40 - 60$ minutes, with very low mass ($0.01 - 0.1$ M$_\odot$) H-depleted degenerate donor stars.

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Table 1
Ultracompact Binary Formation Channels

Formation Channel	Efficiency[a] $P \leq 5\ hrs$	Efficiency $P \leq 80\ min$	Evolutionary History [b]
NS:01	59.4%	60.9%	CE1 CE2 MT2(NS-He/WD)
NS:02	10.4%	10.7%	CE1 MT1 CE2 MT2(NS-He/WD)
NS:03	5.5%	5.6%	CE1 SN1 CE2 MT2(NS-WD)
NS:04	2.4%	2.5%	CE1 MT1 SN1 CE2 MT2(NS-He/WD)
NS:05	0.8%	0.8%	CE1 MT1 MT2 CE2 MT2(NS-WD)
NS:06	0.6%	0.6%	CE1 MT2 CE2 MT2(NS-WD)
BH:01	7.3%	7.5%	CE1 CE2 MT2(BH-WD)
BH:02	4.3%	4.4%	CE1 MT1 CE2 MT2(BH-WD)
BH:03	3.7%	3.8%	CE1 SN1 CE2 MT2(BH-He/WD)
BH:04	3.1%	3.1%	CE1 MT1 SN1 CE2 MT2(BH-WD)
BH:05	1.8%	0.0%	CE1 MT1 SN1 MT2(BH-MS/WD)
BH:06	0.6%	0.0%	CE1 SN1 MT2(BH-MS/WD)

[a]Normalized to the NS/BH UCB population.

[b]Sequences of different evolutionary phases: common envelope CE, mass transfer MT, supernova explosion SN, followed by the digit: 1 stand for the primary (initially more massive component), and 2 for the secondary and these digits mark the donor in CE/MT events, and exploding component in SN. In parenthesis we list stellar types of components at current time during UCB phase: MS– main sequence, He– naked Helium star, WD– white dwarf.

Table 2
Ultracompact Binaries in the Galactic Field

Type[a]	$P \leq 5\ hrs$[b]	$P \leq 80\ min$
NS accretor	79.1% (388)	81.2% (388)
+ donor: WD/He/MS	78.6/0.6/0%	80.5/0.6/0%
NS formed in SN:	8.0%	8.2%
BH accretor	20.8% (102)	18.8% (90)
+ donor: WD/He/MS	18.4/0.0/2.4%	18.8/0/0%
NS formed in SN:	9.2%	6.9%

[a] UCBs with NS and BH accretors are listed. For both groups the relative occurrence frequency of given type of donor (He stand for naked helium star) is given. The number of NSs formed in SN explosions (as opposed to formation through AIC) is also given (all BHs are formed from NS through AIC, however some of these NS are formed in SN, and their number is listed for the BH accretor UCB class).

[b]Relative numbers of systems with orbital period less than P. In the parenthesis the actual number of systems formed in our simulation is given.

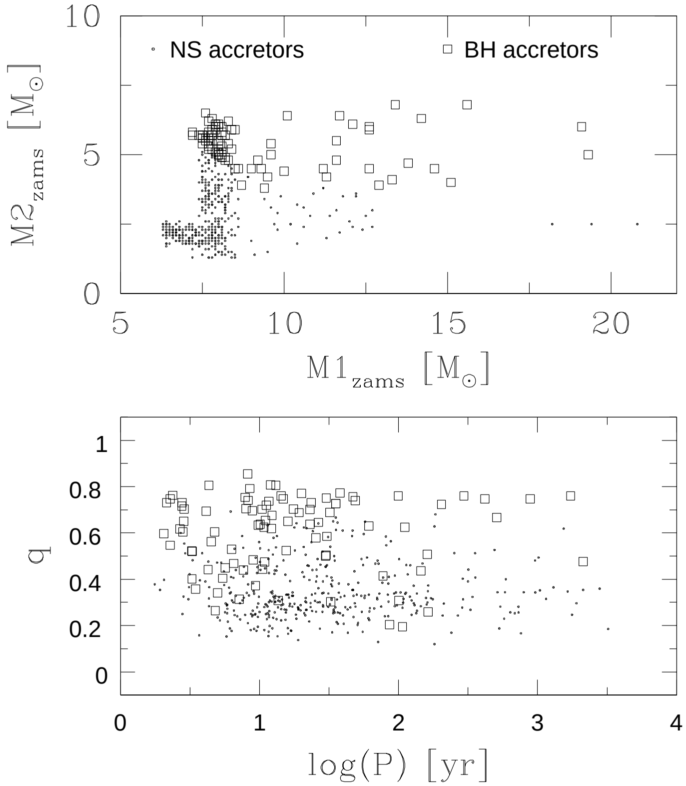

Fig. 1.— Initial binary parameters of UCB progenitor systems. Upper panel shows the correlation between the initial masses of the two binary components, where $M1_{\rm zams}$ and $M2_{\rm zams}$ denotes the initial mass of primary and secondary respectively. The lower panel shows the mass ratios (secondary/primary) versus the initial orbital periods.

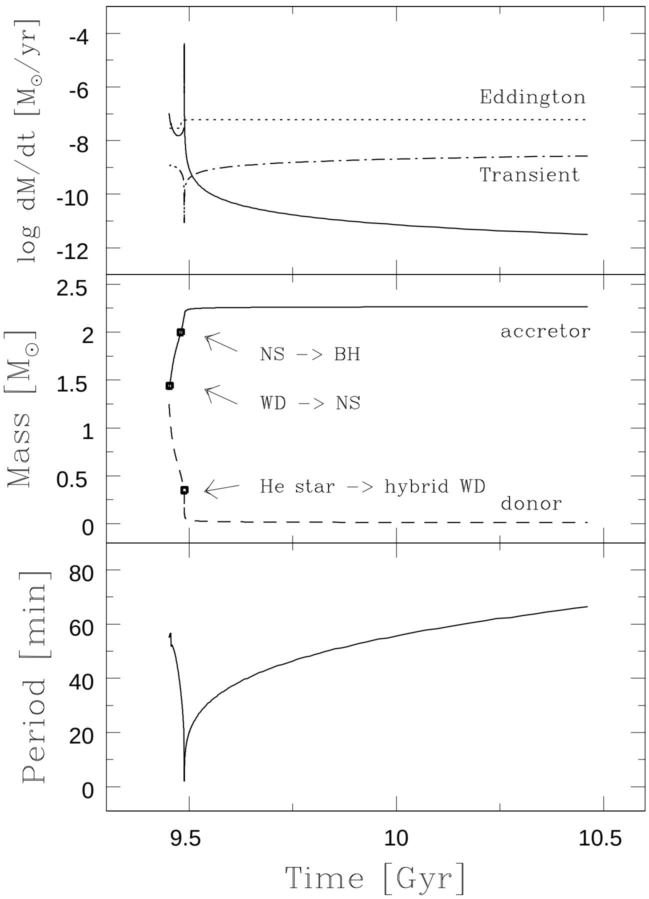

Fig. 2.— An example evolution during the ultracompact phase. The horizontal axis corresponds to the time after the formation of the Galactic disk. The current time corresponds to 10 Gyrs at which time the system is a WD-BH pair (with WD mass of 0.01 M$_\odot$ and BH mass of 2.3 M$_\odot$) at an orbital period of $\sim$ 60 min. The mass transfer rate is $7 \times 10^{-12} M_\odot yr^{-1}$ indicating that the system is a transient X-ray source. Upper panel: The temporal variation of the mass transfer rate is shown as a solid line. The level of critical Eddington mass accretion limit (dotted line) and the critical rate below which system exhibits transient behavior (dot-dashed line) are also shown. Middle panel: The variation of the binary component masses; for the accretor, the two phases of AICs are marked; for the donor we mark the moment it became a WD. Lower panel: The orbital period evolution as a function of time.